INFORMATION SYSTEMS FOR NANOSATELLITE CONSTELLATIONS

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Abstract

This paper describes strategies we are pursuing to address nanosatellite information systems challenges. These challenges are mainly: severely constrained onboard resources, infrequent communications opportunities, and the number of spacecraft that must be managed in future NASA constellation missions. Among these strategies are designing intrinsically autonomous subsystems that operate reliably with minimal processor load. These and other subsystems and tasks will be incorporated into an agent-based infrastructure. A community of onboard and ground-based agents will manage these spacecraft components in a coordinated manner to accomplish a maximal-science goal.

Introduction

Nanosatellite constellations are a double-barreled challenge for information systems. On one hand, the nanosatellite constrains the onboard resources for onboard processing and communications to the ground. On the other hand, constellations require that the information systems simultaneously handle a large number of spacecraft and provide information to the users in an understandable format. This paper discusses these twin challenges and the innovative concepts for addressing them.

Background

NASA is planning missions that would include dozens to hundreds of nanosatellites (nanosats) for future Space and Earth science missions. One of these future missions, used as the example in this paper, is called Magnetospheric Constellation (MC). The MC mission will measure the temporal and spatial details of the magnetosphere by distributing up to 100 10-kg nanosatellites. Figure 1 shows one concept for the orbits of this mission.

The 10-kg mass allocation for each nanosatellite includes the propulsion system and propellant required to place each spacecraft into their proper orbit. The small size of this spin-stabilized spacecraft limits the amount of solar array illumination at any one time.

Power availability is a constraint on both the spacecraft processor and the communications system. The RF system is expected to radiate only about 0.5 watts of power. As a result, the nanosatellites will use omni antennas, without gain, since the spinning spacecraft prevents the use of a pointable antenna. The low power and lack of gain precludes the use of interspacecraft communication to the widely distributed spacecraft and constrains the communications with the ground to only when the spacecraft is near perigee.

The number of spacecraft in the constellation drives some of the constraints on the information system. However, the redundancy of a large constellation offers opportunities as well. The large number of identical spacecraft allows the mission to accept an increased risk associated with individual elements of the constellation.

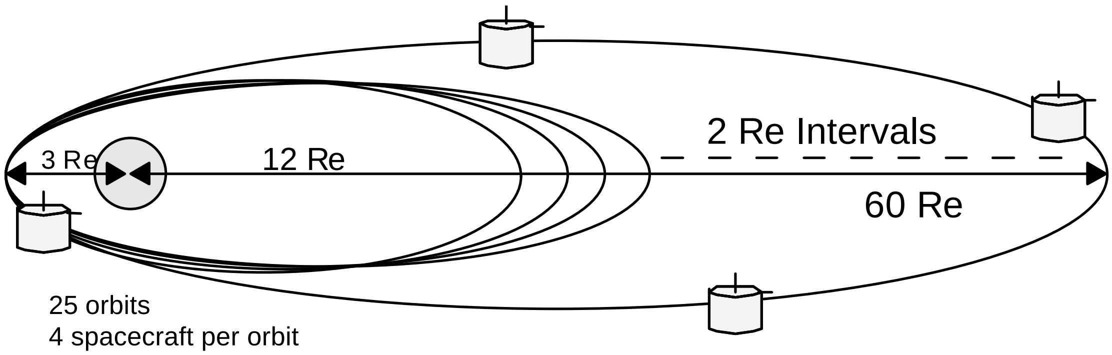

Figure 1. Magnetospheric Constellation Orbits

The MC mission is presently the focus of our current technology efforts. These technologies are expected to be applicable to other Space and Earth science constellation missions.

Onboard Information System Concepts

Nanosat spacecraft may be out of contact with the ground for over a week. The limited communications opportunities and limited bandwidth impose constraints on data handling, fault detection and correction and instrument commanding in general. As a result, the craft need to operate autonomously and handle any anomalies or opportunities that occur. This autonomy must be accomplished within a processing capability that is less powerful than could be accomplished on spacecraft without the weight and power constraints of the nanosat.

Limited nanosat resources preclude the use of redundant systems. This constraint affects how the single-string systems are designed and operated in order to maximize scientific return.

Strategies

Although the nanosat spacecraft will incorporate reduced processing capability relative to typical spacecraft and no redundant systems, this does not imply the nanosat must be less capable. It does require us however, to consider novel perspectives and strategies that allow us to accomplish ‘more with less’.

Our objective is to incorporate intelligence onboard the spacecraft so that minimal ground support is required. The onboard control actions required to support this paradigm range from simple timer-based strobes to more substantial tasks that require reasoning.

In all cases, however, subsystems will be designed to be as autonomous as possible. Each subsystem will know only about its own status. A more comprehensive intelligence will integrate the states of all subsystems into a master view of the spacecraft state. This will allow the effects and influences of various subsystems on each other to be recognized and handled in appropriate ways.

In an agent community architecture (Figure 2), this type of integration is easy to realize. An agent associated with each subsystem will assess the subsystem state and intervene when the subsystem is incapable of handling a problem. It will also manage the subsystem based on higher-level directives issued by the spacecraft agent.

The spacecraft agent will maintain a dialog with the subsystem agents to gather information that will allow it to ascertain an overall view of the spacecraft state. It will use this information to provide directions to task agents in case the operation of the responsible subsystem should be modified to maintain the spacecraft objectives.

We plan to conserve onboard bandwidth and power by minimizing data flow to and from the spacecraft processor. This will be done designing certain systems to intrinsically incorporate a high degree of autonomy and fault tolerance; as little processor control as reasonable will be required.

Conversely, some tasks or subsystems will be processor intensive. The science instruments and the transmitter for example, will communicate with the processor at high rates during certain periods. The nanosat infrastructure will be capable of efficiently supporting both the minimal and maximal extremes.

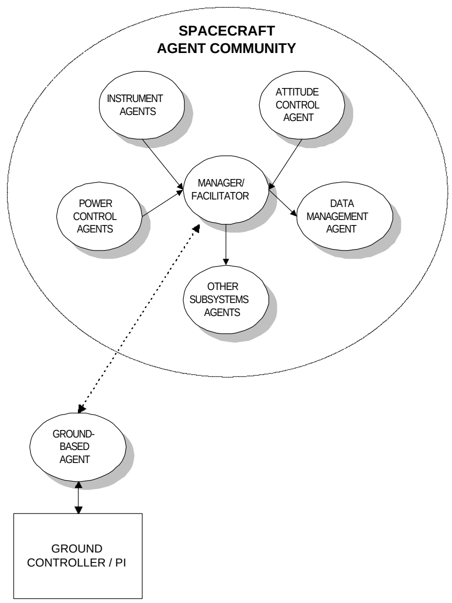

Figure 2. Onboard Autonomy Concept

Intrinsic and Distributed Autonomy

One fairly common design philosophy involves relocating intelligence from a subsystem to a central controller. The controller would then manage the subsystem based on feedback and commands. Where practical, we are attempting to implement the other extreme; design subsystems with a minimal number of operational modes, e.g. off, start and on, robust enough to accommodate wide ranges of external stimuli. The power supply electronics and the thermal control subsystems for example, will satisfy this criteria. Intrinsically reliable hands-off operation will result from architectures devised from the onset to support this paradigm.

Conversely, some other tasks will require more central processor-based reasoning to accomplish their goals. Among these are data management, orbit determination.

Science Phenomena Identification

Data signatures developed by scientists to identify phenomena of interest, can be used by an agent to assist in data processing and science instrument management. In order to use the limited downlink bandwidth most efficiently, both engineering and science data can be edited onboard. Engineering data can be summarized and sent to the ground at much lower sampling rates than is available onboard. In the event of an anomaly, the spacecraft could save a snapshot of the full resolution telemetry data. Certain parts of the orbit will be of be deleted, sampled at a lower rate, or compressed for these areas of the orbit.

Onboard agents could prioritize data. There will be times when all of the data cannot be sent to the ground due to conflicts with other members of the constellation. The onboard system will prioritize the data to ensure that the most scientifically interesting data is downlinked first, so that any data that must be overwritten is of lower priority. The intelligent onboard system will identify some of the high priority data by detecting signatures of interesting phenomena (e.g., substorms) in the data.

Onboard Orbit Determination

In addition, GSFC is exploring other onboard functions that would allow future constellations to be fully autonomous - to be flown without a receiver. This would require a capability for the onboard system to identify the appropriate downlink time (through onboard orbit determination or other methods) since the satellites are within communications range of a ground station only as they near perigee (Figure 1).

Agent Infrastructure

We are investigating a generic framework for implementing these diverse goals. The current concept calls for a hierarchical community of agents who monitor the various subsystems and report to a facilitator or manager who is responsible for interfacing with a ground system as needed.

This infrastructure will enable a nanosat to use the high level science goals to plan and execute reactive or proactive measures based on system state or trends, maximize science return in spite of instrument subsystem anomalies, and modify ongoing science observations based on science data content.

The agent architecture we are investigating is a component architecture. This architecture provides a great deal of flexibility to the designers of agents. A simple agent can be designed using a minimum number of components that would receive percepts from the environment and react according to those percepts. A robust agent may be designed to use many components that allow the agent to perform sophisticated reasoning, planing, scheduling, modeling the environment, and learning. The architecture shown in Figure 3 focuses on an agent that is on the highly robust side of the scale; it contains components for reasoning, modeling, and planning. These components give the agent a higher degree of intelligence when interacting with its environment.

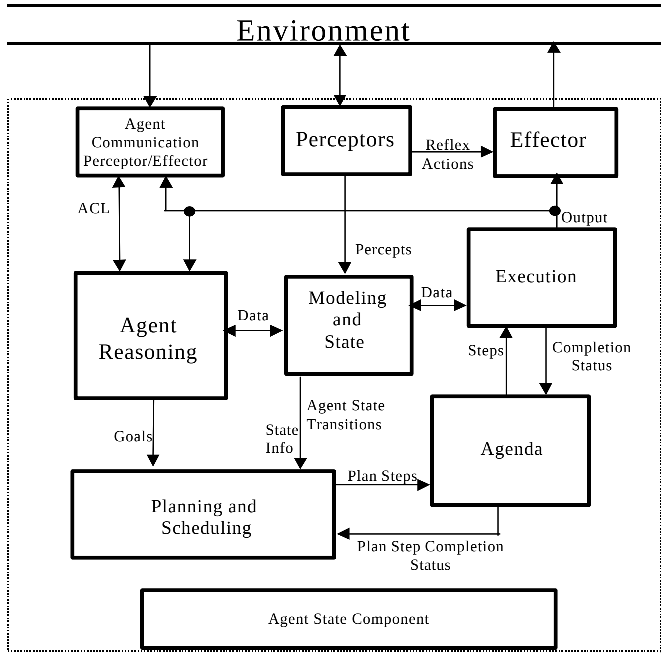

Figure 3. A generalized Robust Agent with Planning, Modeling and Reasoning Capabilities

The Perceptor component receives percepts (inputs) through sensors and by communicating with external software/systems and agents. These percepts are passed from the perceptor to Reasoning, Modeling and State components where a model's state is updated as needed. A special perceptor, the Agent Communication Perceptor/Effector, is used to send and receive messages with other agents. Additionally, incoming Agent Communication Language (ACL) messages are formatted and passed to the Agent Reasoning component. The Agent Reasoning component utilizes the percept information, received ACL messages and the knowledge that it contains, and information that is acquired from the Modeling and State component to formulate goals for the agent. Goals are then presented to the Planning component along with state and state transition information.

The Planning component formulates a plan (a sequence of steps) necessary for the agent to achieve the desired goals. When a plan has been developed, the Agenda keeps track of the execution of the plan's steps. Steps are marked when they are ready for execution and the completion status of each step is also tracked by the Agenda. The Execution component manages the execution of steps and determines the success or failure of each step's execution. Output produced during a step execution can be passed to an Effector or the Reasoning component. The Modeling and State component will record state changes. When a plan is finished execution, a completion status is passed to the Planning component for evaluation of the plan for future use.

We call the reasoning concept we are investigating multi-modal reasoning in that it will incorporate rule-based, case-based and model-based reasoning techniques.

A generic framework will capture knowledge about the structure and behavior of the spacecraft subsystems. The agents will use this framework to reason about the health and safety of each system and take action as needed. The agents will also manage their science agenda by reasoning about the science and engineering data associated with the instruments.

Ground Information System Concept

Current science mission ground systems manage individual spacecraft. This will not be feasible for constellations. The constellation ground system will have to allow users to interact with the mission as a constellation for many functions: status, commanding, flight software updates, and science data. In addition, it must allow a user to look at an individual spacecraft for anomaly investigation. Figure 4 illustrates ground information system concepts.

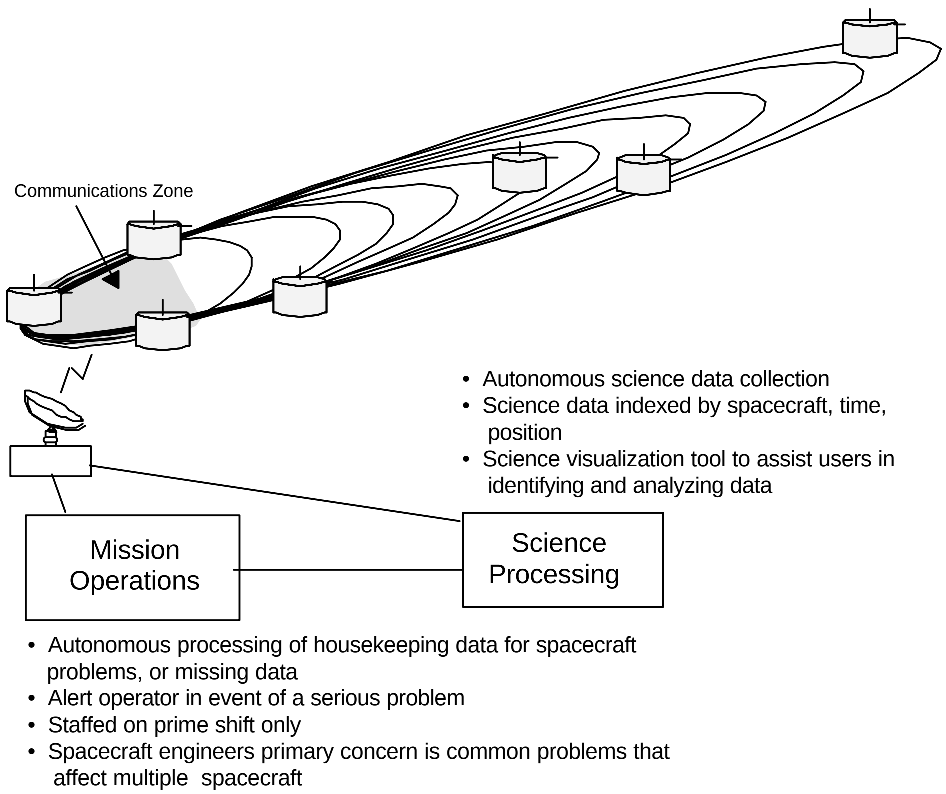

Figure 4. Ground System Design

The ground system must be able to communicate with multiple spacecraft simultaneously. At times, over a dozen spacecraft could be near perigee simultaneously. The ground system will need to be sized to accommodate enough of the spacecraft to meet the data completeness goals of the mission (~95%). For the nanosat constellations, the ground system will consist of a network of relatively large antennas. The ground system must autonomously schedule the ground stations to optimize the data return. The scheduling algorithm will include a number of factors in resolving conflicts among the members of the constellation. Each spacecraft's priority will include the amount of data loss if not scheduled and the importance of the data from the mission point of view. For example, it may be acceptable to lose data from a particular spacecraft if data from other spacecraft in similar orbits has been received. The scheduling system must autonomously reschedule the contacts to accommodate missed contacts or other operational problems.

The ground system needs to collect the status of all members of the constellation and perform autonomous fault detection and prioritization. This triage process allows the small ops team to concentrate on the priority problems with the constellation. An agent architecture is one possible implementation of the ground system. This implementation would be common with the spacecraft agent implementation. A constellation agent can accept the status of all of the spacecraft agents and provide a unified, prioritized list of status and anomalies to the operations team. Constellation health and safety problems would have the highest priority, followed by individual spacecraft health and safety, data delivery problems (both telemetry to the ground and commands or loads to the spacecraft), and tracking data problems.

The redundancy in the mission protects it from random failures but makes it vulnerable to design flaws. The ground information system will have trending tools to examine status data across spacecraft as well as across time, to look for common problems across spacecraft. The tools would compare problems to identify if they were similar to previous problems. Later in the mission, once a problem data base has been established, the ops staff could benefit from the redundancy of the constellation, and accept some failures without intensive analysis of the cause of the failure.

The information system requires data visualization techniques for both engineering and science data analysis to allow users to integrate the information from a large number of sensors. The science data will be organized to allow users to access data by location and time, without having to sort through individual spacecraft data sets.

End-to-end Information System Concepts

The autonomy architecture for a nanosatellites will encompass both the onboard system and the ground system. This will allow the ground system and the spacecraft to synchronize their operation without operator intervention. A common architecture will also enable the migration of functions from ground to space.

The agents in the framework are as simple or as complex as reasonable. Conditions that cannot be handled onboard agents will be referred to the ground-based agents. They will incorporate greater capability than the onboard agents will since they will not be limited by the sciencecraft mass and power constraints. Additionally, historical knowledge of the states and the actions taken by each craft in the constellation will reside within the ground system knowledge base by virtue of the data dumps made during each contact. The agents can use this knowledge to detect trends and systematic conditions not otherwise observable onboard the spacecraft.

Since limited power resources do not permit direct communication member of the constellation, this function can be implemented via the ground-based agent. Limited communications opportunities will impose scheduling constraints however.

Summary

Nanosatellite constellations impose unique challenges and opportunities on the end-to-end data system. GSFC is using the MC mission concept to assist in the definition of these challenges and the technologies required to address them. A number of concepts have been identified and are in the process of being demonstrated.

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Biographies

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